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## Lifetime and magnetic moment measurements

V. Werner<sup>1</sup>, G. Ilie<sup>1,2</sup>, D. Radeck<sup>1,3</sup>, T. Ahn<sup>1</sup>, C.W. Beausang<sup>4</sup>, L. Bettermann<sup>1,3</sup>, R.J. Casperson<sup>1</sup>, R. Chevrier<sup>1,5</sup>, N. Cooper<sup>1</sup>, T.C. Bonniwell<sup>4</sup>, A. Heinz<sup>1,6</sup>, E. Holland<sup>1</sup>, D. McCarthy<sup>1,7</sup>, B. Pauerstein<sup>4</sup>, M.K. Smith<sup>1</sup>, J.R. Terry<sup>1,8</sup>, E. Williams<sup>1</sup>

<sup>1</sup>Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA

<sup>2</sup>National Institute for Physics and Nuclear Engineering, P.O. Box MG-6, Bucharest-Măgurele, Romania

<sup>3</sup>Institut für Kernphysik, Universität Zu Köln, D-5037 Köln, Germany

<sup>4</sup>Department of Physics, University of Richmond, Richmond, Virginia 23173, USA

<sup>5</sup>Department of Physics, University of Caen Basse-Normandie, 14000, France

<sup>6</sup>Chalmers University of Technology, Department of Fundamental Physics, 41296 Goteborg, Sweden

<sup>7</sup>Department of Physics, University of Surrey, Guilford, GU27XH, United Kingdom

<sup>8</sup>Los Alamos National Laboratory, Los Alamos, NM, USA

E-mail: volker.werner@yale.edu

**Abstract.** The g-Plunger technique has been introduced, which allows for the simultaneous measurement of lifetimes and absolute values of g-factors using a plunger device in inverse kinematics. Experiments on the <sup>104,106,108</sup>Pd isotopes using Coulomb excitation resulted in g-factors in agreement with literature data. Lifetimes of 2<sub>1</sub><sup>+</sup> states have in part significantly changed in this work.

### 1. Introduction

Plunger devices for lifetime measurements in combination with the Recoil Distance Doppler Shift (RDDS) method have been used since many years [1]. Great advances were achieved through the introduction of the Differential Decay Curve Method (DDCM) [2], and modern Cologne-type plunger devices became a standard, which ensure a fixed distance through capacitive feedback [3], such as the (“new”) Yale Plunger Device (NYPD) [4]. With the application of many methods to inverse kinematics as a consequence of the increased use of rare isotope beams, also the effects of nuclear deorientation in plunger experiments, as discussed, e.g., in [5, 6], needs to be re-addressed. In contrast to normal kinematics reactions, in inverse kinematics, due to the high charge states reached using fast heavy beams, deorientation effects become important in the regime of few-picosecond lifetimes. Whereas deorientation leads to the necessity of corrections in RDDS analyzes [10, 11], we show that it can be effectively used to obtain relative magnetic moments for excited nuclear states, applying techniques developed in normal and inverse kinematics (see, e.g., Refs. [7, 8, 9]).

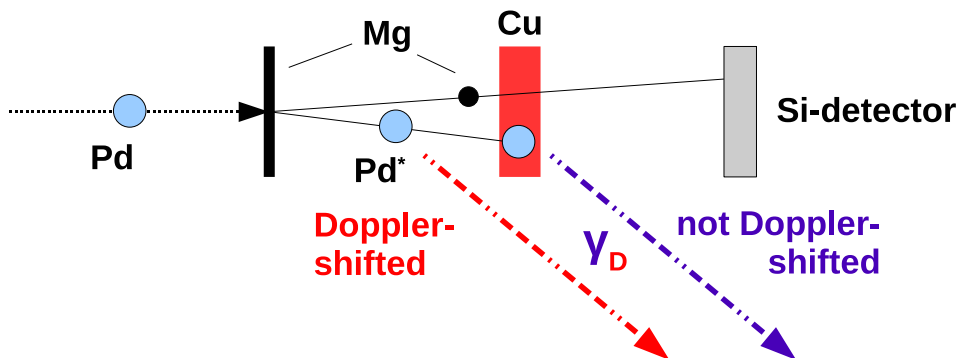
We chose <sup>106</sup>Pd and neighboring Pd isotopes to test the technique to measure excited state lifetimes and relative g-factors in parallel, henceforth referred to as g-Plunger technique. The g-factor of the first excited 2<sup>+</sup> state,  $g(2_1^+)$  in <sup>106</sup>Pd, is well established [12] and serves as a reference point for much other g-factor data in this mass region [13]. In the following, the

method to fix parameters of the hyperfine interaction and use them to obtain g-factors will be outlined. Preliminary results on  $^{104-106}\text{Pd}$ , for lifetimes and g-factors of their  $2_1^+$  states will be given.

## 2. The g-Plunger technique

### 2.1. Experiment

We chose the Coulomb excitation mechanism in order to directly populate only the first excited  $2^+$  state of even-even nuclei, in this case  $^{104-108}\text{Pd}$ . At a sufficiently low beam energy, feeding from higher-lying states is negligible, tremendously simplifying the RDDS analysis. A scheme of the plunger setup is shown in Fig. 1. The heavy-ion beams at energies of 324 MeV, 330 MeV, and 336 MeV, respectively, were produced by the ESTU tandem accelerator at the Wright Nuclear Structure Laboratory (WNSL) at Yale University. The beams were Coulomb-excited on an about  $0.6 \text{ mg/cm}^2$  thick  $^{24}\text{Mg}$  target, and subsequently stopped in a  $15.7 \text{ mg/cm}^2$  thick Cu foil. The distance between the foils within NYPD was varied between electrical contact to about 2 mm. Coulomb-excited Pd nuclei decayed either in flight in between the two foils, or after stopping in the Cu foil. Hence, two components of the decay were visible in the spectra, Doppler shifted and unshifted.  $\gamma$ -rays were detected by anti-Compton shielded detectors of the YRAST-Ball array [14] in the SPEEDY setup [15], 3 placed at  $138.5^\circ$ , 4 at  $41.5^\circ$ , and an additional 2 unshielded clover detectors at  $90^\circ$  relative to the beam axis. The forward scattered Mg nuclei passed through the Cu foil and were detected in a Si detector behind the stopper. The requirement of a coincidence between the Si detector and any HPGe detector along with random-background subtraction ensured excitation on the target and not on the stopper foil, and removed all contributions from room background.



**Figure 1.** Schematic of the setup inside the plunger target chamber.

### 2.2. Lifetime analysis

The data was analyzed by fitting the in-flight decay probability

$$P_{\text{exp}}(d) = \frac{I^{SH}(d)}{I^{SH}(d) + I^{USH}(d)}, \quad (1)$$

obtained from fitting the Doppler shifted and unshifted peaks, after applying corrections to the measured peak areas. These corrections were due to solid angles of the HPGe detectors, introducing-factors  $Q_k$  [16] into the angular distribution function of the  $\gamma$ -rays, as well the solid angle of the particle detector, which was taken into account in calculations using a standard Coulomb excitation code [17]. A significant correction due to the large velocities ( $4\% c$ ) is from

the Lorentz boost, which changes the effective detection solid angles for Doppler-shifted  $\gamma$ -rays (laboratory system versus nuclear inertial system) following

$$\frac{d\Omega}{d\Omega'} = \left( 1 + \frac{E_\gamma - E_{\gamma,0}}{E_{\gamma,0}} \right)^2 . \quad (2)$$

Another major correction is due to the deorientation effect, which is discussed in the following sub-section. Since Clover detectors, consisting of four individual crystals, can be split into two halves with different angles relative to the beam axis, we obtained data for a total of six angles (rings). For each ring we fitted  $P_{\text{exp}}(d)$  with the decay function

$$P(d) = A \cdot (1 - \exp(-\lambda(d - d_0))) , \quad (3)$$

where  $A$  is a scaling parameter, and  $d_0$  is the minimum achievable distance setting (just before electrical contact between the foils), which was independently obtained from a distance calibration, and from this fit. The lifetime of the  $2_1^+$  states was extracted using  $\lambda = \frac{1}{v \cdot \tau}$ .

For the first excited state of  $^{106}\text{Pd}$ , a preliminary lifetime result is  $\tau(2_1^+, ^{106}\text{Pd}) = 19.87(14)$  ps, where the error is purely statistical. We currently assume another 1-2% systematic error. We note, that the result before deorientation correction is about 17.6 ps, making this correction the most important one in the lifetime analysis. It is due to the fact that nuclei decaying from their  $2_1^+$  state in the stopper foil, passed through the entire vacuum gap between the foils, in which they lost their alignment due to the hyperfine interaction. In contrast, nuclei decaying in-flight only passed through a fraction of the vacuum distance in their excited state, hence, the angular distribution of the de-exciting  $\gamma$ -rays is less attenuated.

### 2.3. Nuclear deorientation

After Coulomb excitation, nuclei leaving the target are aligned with respect to the beam axis, hence,  $\gamma$ -rays from decays of the  $2_1^+$  state have a distinct angular distribution. However, after leaving the foil they are subject to hyperfine interaction, which causes a precession of the nuclear spin  $\vec{J}$  around the total spin of the ion  $\vec{F} = \vec{J} + \vec{I}$ , where  $\vec{I}$  is the atomic spin. Since the atomic configurations of the ions after passing through the target (Mg) foil are randomized, the directions of the precessions are random. Assuming that the atomic state lifetimes are longer than the deorientation process, one expects an approximately exponential attenuation of the alignment of the ensemble of nuclei, converging to a hard-core value [6, 7, 18]. This behavior is parametrized in factors

$$G_k(t) = \alpha_k + (1 - \alpha_k) \cdot \exp(-\Gamma_k t) , \quad (4)$$

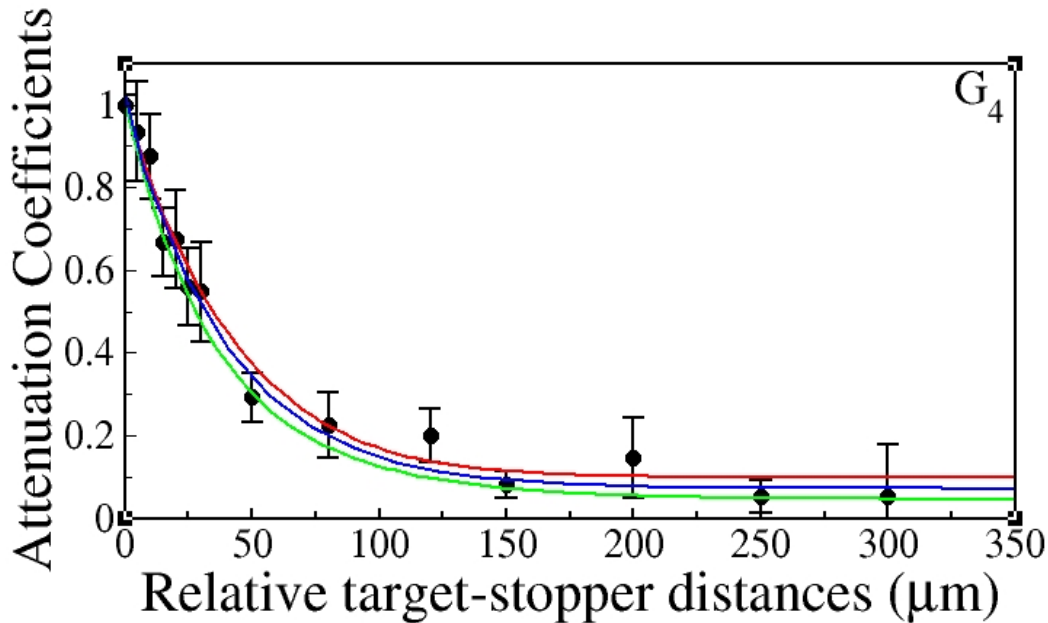
which are introduced into the  $\gamma$ -ray angular distribution function as

$$W(t, \vartheta) = \sum_{k=0,2,4} R_k B_k Q_k G_k(t) P_k(\cos(\vartheta)) . \quad (5)$$

Herein,  $R_k$  coefficients follow the convention of Rose and Brink [19], and  $B_k$  coefficients correspond to the initial alignment ( $d = t = 0$ ), which is calculated from the Coulomb excitation mechanism;  $P_k$  are Legendre polynomials. The  $G_k$  parameters ( $k = 2, 4$ ) are obtained from the ratios of the experimental angular distribution parameters  $A_k = R_k B_k Q_k G_k$  at each distance over the unattenuated values as obtained from the Coulomb excitation formalism,

$$G_k(t) = \frac{A_{k,\text{exp}}(t)}{A_{k,\text{coulex}}(t = 0)} . \quad (6)$$

A fit of Eq. (4) to the experimental  $G_k$  coefficients then gives the hard-core parameters  $\alpha_k$ , as well as the time constant of the exponential,  $\Gamma_k$ . A sample fit is shown in fig. 2. The parameters



**Figure 2.** Sample deorientation fit from the  $^{106}\text{Pd}$  data, showing the attenuation of the 4<sup>th</sup> order term in the angular distribution function (5).

$\Gamma_k$  depend on the g-factor of the excited state,

$$\Gamma_k = \frac{|g|}{C_k}, \quad (7)$$

where  $C_k$  are parameters of the hyperfine interaction. We used the known g-factor  $g(2_1^+) = +0.398(21)$  for  $^{106}\text{Pd}$  to extract the parameters  $C_k$ . Since a change of the hyperfine interaction is not expected for neighboring Pd isotopes after the same reaction, hence, charge state distribution,  $C_k$  can be assumed to be the same for all Pd isotopes. For the data on  $^{104,108}\text{Pd}$ , we hence left  $|g|$  as a free parameter and obtained g-factors for the  $2_1^+$  states of both isotopes. Preliminary results are given in Table 1, compared to literature values. We note that the statistics in the  $^{104}\text{Pd}$  case was low, leading to the larger error bar. Also, only absolute values of g-factors can be obtained in the g-Plunger technique.

### 3. Discussion

The g-factors obtained in this work agree within error with literature values. Hence, the g-Plunger technique offers a technique alternative to the commonly used transient field technique (see, e.g. Ref [20] for the measurement of magnetic moments of short-lived excited states. The advantage of the method over RIV is the possibility of a time dependent measurement. Whereas in RIV g-factors and lifetimes of excited states in multiple isotopes of an isotopic chain must be known to parametrize the hyperfine interaction, the same can be obtained in one isotope for which only the excited state g-factor needs to be known. Lifetimes and g-factors can be measured simultaneously using a plunger device. The g-Plunger technique only gives absolute values of g-factors, akin to RIV. Measuring the sign of a g-factor needs the application of an external field, such as in the transient field technique.

**Table 1.** Preliminary results: absolute values of the g-factors of the  $2_1^+$  states in  $^{104,106,108}\text{Pd}$ . The value marked with an asterisk\* was used as a reference point. Errors for values from the present work are statistical only.

	$^{104}\text{Pd}$	$^{106}\text{Pd}$	$^{108}\text{Pd}$
$ g(2_1^+) $			
this work:	0.52(10)	0.40(2)*	0.32(5)
NNDC:	0.46(4)	0.40(2)	0.36(3)
$\tau(2_1^+)$			
this work:	15.64(18) ps	19.87(14) ps	39.05(67) ps
NNDC:	14.9(9) ps	17.6(6) ps	34.6(18) ps

The lifetime values obtained in this work are systematically higher than literature values. The difference to literature values was in all cases introduced when applying the deorientation correction to the data. Problematic is especially the change in  $\tau(2_1^+)$  of  $^{106}\text{Pd}$ . If the literature lifetime value is changed to our present value, the g-factor of the state will have to be reanalyzed. This would potentially lead to a change of all g-factors that have been measured relative to the  $g(2_1^+)$  factor in  $^{106}\text{Pd}$ . We are currently reanalyzing the data in order to exclude any systematic errors in the analysis procedures, and are analyzing data sets on other isotopic chains. One recent experiment on  $^{98}\text{Ru}$  using the g-Plunger technique has just been submitted for publication [21]. No significant change in the  $2_1^+$  lifetime has been found in that case.

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